AADE 01-NC-HO-52

Embedment Modulus of Mudcakes - Its Drilling Engineering Significance

Md. Amanullah and C.P. Tan, SPE, CSIRO Petroleum

Abstract

A test facility and a novel laboratory technique have been developed for mechanical assessment of mudcakes to predict the embedment resistance of mudcakes formed by different mud systems. An index parameter 'Embedment Modulus' defined as the secant slope of the driving force vs. embedment area curve, obtained by driving a cylindrical foot into the mudcake matrix at a predefined rate of embedment was used for mechanical assessment of mudcakes formed by various mud systems.

The newly developed test set up consists of a Wykeham Farrance stepless compression machine to apply a normal load on the mudcake, a digital dial gauge to register the depth of embedment, an electronic balance to register the embedding load as a function of time and depth, a lab jack to elevate the mudcake to a desired height and a PC-based automatic data acquisition system to monitor the test.

Experimental results indicate wide variation in the embedment resistance of mudcakes with the variation of the composition of the cake forming mud systems. The presence of some electrolyte significantly reduces the embedment resistance of bentonite mudcakes. The results indicate that the presence of ions and also the type of ions have a remarkable influence on the cake matrix rigidity. The presence of barite causes an increase in the embedment resistance of mudcakes probably due to the pore filling effect of barite particles. The effects of anionic, polyanionic and non-ionic fluid loss additives such as CMC, PAC and modified starch on salt water-based mudcakes have also been investigated. The presence of PAC in a mud system causes a significant increase in embedment modulus than the presence of CMC.

The results of the test could provide useful information for mechanical assessment of drilling mud systems and select a suitable mud to minimise the potential of pipe sticking and embedded cuttings beds formations in case of directional and horizontal wellbores.

Introduction

A mudcake is formed on the wall of boreholes due to the deposition of mud particles and formation of a network of structures of colloidal and non-colloidal particles enclosing fluid-filled voids or inter-spaces of varying sizes during the period of circulation and non-circulation. The mechanical properties of mudcakes such as coefficient of friction, erodability, lift-off pressure, embedment resistance, adhesion properties etc. have direct relation with different types of mud-related borehole problems. Even though significant advances have been made in the design and formulation of drilling muds to produce mudcakes with acceptable properties, the advent of deeper, horizontal, slim hole and coiled tubing drilling increased the scope of mud and mudcake related borehole problems. The physio-mechanical properties of different mudcakes can differ greatly from one another due to the variation in physical, chemical and electrical properties of mud additives forming the mudcake and the nature of interactive forces prevailing during the period of deposition. Harden and Welch[1] reported laboratory results showing variation of forces necessary to move a piece of steel pipe on the filter cake with a variation in the composition of the mudcake. Although different borehole problems are associated with the mechanical characteristics of mudcakes, little attention has been paid to develop a suitable methodology for determining the mechanical characteristics of mudcakes formed by different mud systems. Mudcake with lower embedment resistance will increase the pulling or running load of pipes, especially in directional and deviated wellbores, due to an increase in mudcake-pipe contact area. According to Amanullah and Tan[2], muds producing soft and thick mudcakes increase the potential of differential sticking and thus not desirable for geological formations highly prone to differential sticking. Mudcake properties such as thickness, lubricity and strength are some of the factors which increase the scope of differential sticking (Reid et al.[3]). Isambourg and Matri[4] also pointed out mudcake hardness as one of the parameters which govern differential pressure sticking problem. Mudcake properties may also influence the scope of bit and BHA balling. According to Warren[5], bit and/or BHA balling may occur as a result of the accumulation of filter cake on the bit or BHA during pulling a drill string. The scope of this accumulation is higher for softer mudcakes than harder mudcakes.

As no hole is truly vertical and the drill string is not perfectly rigid, the rotating drill pipe can contact the deposited mudcake at numerous points of the borehole during the drilling operation. The degree of embedment during this momentary contact depends on the dogleg severity of the borehole profile and the embedment resistance of the mudcake. When the rotation of the drill string is stopped, the normally acting nominal weight of the pipe compresses the contacted mudcake, breaks the cake forming structural units, forces its matrix fluid out of the cake and embeds into the cake. Cake with a low embedment resistance will cause a higher embedment of pipe into the mudcake with the generation of a higher frictional resistance and adhesive bonding between the mudcake and the pipe. The interplay of frictional resistance, cohesive and adhesive bonding will provide higher resistance to drill string motion and thus will require an extra torque to rotate the bit or additional force to pull a stuck pipe or run a casing or a drill string. Maidla[6] showed how mudcake can influence the casing running load in the wellbores. The neutralisation of some of the weight of the drill string by the upward drag resistance of the mudcakes will also cause a reduction in WOB (weight on bit) and ROP (rate of penetration).

In case of deviated and horizontal wells, a portion of the drill string lies against the low side of deviated or horizontal holes. This part of the string when comes in contact with the mudcake, applies a normal load on the mudcake surface which varies depending on the hole angle and the area of the pipe coming in contact with the mudcake. The degree of embedment of the pipe will depend on the mechanical properties of the cake and thus will be an important factor in determining the torque and drag necessary for rotating a string, pulling out of hole and running into the hole. During static condition, progressive embedment of the pipe will be higher for low resistance mudcakes than high resistance mudcakes.

Drill cuttings have a tendency to form a cuttings bed on the low side of deviated and horizontal boreholes during the period of non-circulation. The cuttings bed can also be formed during the period of drilling if the annular velocity is low. In this case, there is a high possibility of impregnation of drill cuttings into the mudcake matrix, especially the larger cuttings. The degree of cuttings impregnation will vary depending on the embedment resistance of the mudcake and the size of the cuttings. The cuttings will impregnate more in the presence of mudcake with low embedment resistance compared to a hard and high resistant mudcake. Hence, the scope of pipe sticking due to cuttings pack-off will be significantly higher for low resistant mudcake. Greater pulling and running forces, and also torque will be required to move the pipe upwards or downwards or rotate. As the cuttings-impregnated mudcake will apply a higher frictional resistance, the required pulling force can easily exceed the rig capacity. Hence the embedment characteristic of mudcake can provide useful information to design a mud system for deviated and horizontal wells. The greater depth of pipe embedment in mechanically weaker mudcakes produces intimate contact between the pipe and the mudcake and thus enhances the participation of the so called adhesive forces to contribute to the total frictional resistance during pulling a stuck pipe. In the presence of mudcake with low embedment resistance, the hole cleaning will also be more difficult and complicated due to the formation of a highly impregnated cuttings bed. In this case, the hydrodynamic forces of mudflow and the rotating pipes may not be sufficient enough to dislodge the impregnated cuttings and transport them back into the bulk flow stream of the mud.

In case of coiled tubing drilling, the pipe will be in physical contact with the borehole wall for an extended length of the hole. In the presence of a mudcake with low embedment resistance, the tubing will be buried deeper into the mudcake which will increase the frictional and adhesional resistance due to an increase in tubing-mudcake contact area and the angle of contact between the mudcake and the tubing. The potential of excessive sliding friction will increase the possibility of helical lock-up of the pipe, leading to a reduction in further progress in making a hole. Hence, a mud system producing a mudcake of lesser thickness and higher embedment resistance will be more desirable for coiled tubing drilling.

Currently no suitable quantitative method is available for mechanical characterisation of mudcakes. Sometimes qualitative assessment is made by pressing a mudcake with a fingertip which is very subjective, has high human error and thus is not suitable for proper assessment of a mud system. Qualitative ranking of mudcakes such as very soft, soft, medium hard, hard are done on the basis of personal judgement. According to Davis et al[7]., guidelines on evaluation of mudcake quality such as thickness, hardness and stickiness have always been crude and made characterisation of mudcakes a very subjective process. Hence, a semi-quantitative or a quantitative assessment tool is needed for better evaluation of the mud quality compared to the qualitative method. The quantitative assessment needs some kind of laboratory testing for estimating the mechanical property of the mudcakes which can conveniently be used for comparison of mudcakes formed by different mud systems. This paper describes a novel laboratory technique for mechanical characterisation of mudcakes formed by different mud systems.

Concept of Embedment Resistance and Modulus

Most mud additives carry either a positive or a negative electrical charge. Some mud additives such as bentonite may have both positive and negative electrical charges and others may be non-ionic in nature. Some mud additives such as polymers may have both electro-chemical and physical bonding potential. Physical bonding capability varies from polymer to polymer, some have single point bonding potential and others have multi-point bonding potential with themselves and other mud additives. Due to the charged nature of most mud additives and interplay of other forces such as van der Waals, hydrogen bonding forces and also their variation with the composition, pH and nature of ionic species presence in the mud, they produce mudcakes with wide variations in structural units, permeability and matrix rigidity. The ultimate rigidity of the mudcake is the net resultant effect of these interactive forces. If the resulting effect of these forces of interaction is strongly attractive in nature, then the mudcake is very hard. If the resultant effect is a very weak attractive force, then the mudcake is very soft.

Any object pushing into a mudcake will encounter resistance during its downward movement in proportion to its matrix rigidity (see Figure 1). The magnitude of this resistance force will depend on the active area of the mudcake resisting the object, the rate of displacement of the object, structural rigidity of the cake fabric units and permeability of the mudcake. For a constant foot-cake contact area and rate of displacement of the object, the magnitude of the resistance will vary depending on the matrix rigidity and permeability of the mudcake. This is due to a wide variation in the bonding potential of different mud additives in different depositional conditions. The total resistance offered by a cake matrix to resist the movement of an object is defined as embedment resistance. The force require to drive the object will be proportional to the embedment resistance of the mudcake. Hence, the determination of the driving force to reach a particular depth or embedded area will provide a good indicator for the embedment resistance of mudcakes formed by different mud systems. The slope of a suitable part of the driving force versus embedded area curve may be used as the embedment modulus (EM) of a mudcake. Here the embedment modulus is defined as the secant slope of the line passing though the origin and the point representing an embedded area equal to 1000 mm^2.

Preparation of Mudcakes

Because of the objective of the study was to make comparative assessment of different mudcakes formed by various mud systems, the muds were designed using common mud additives and the least number of mud chemicals. The formulation of the muds is given in Table 1. These additives are used to generate good rheological and cake building potential by forming a good, non-erodable, tough and low permeable mudcake on the borehole wall. The mudcakes were prepared using an API filter press by running the filtration test for a period of time to produce 100 cc filtrate. Preliminary study indicated that most muds used for this study will produce mudcake above 14 mm thick for a filtrate volume of 100 cc. Mudcakes were prepared with and without barite, using different salts and ionic polymers to assess their effect on the mechanical properties of mudcakes. Anionic, polyanionic and non-ionic fluid loss additives were used to assess their potential of producing mudcakes with higher matrix rigidity. The selected salts, fluid loss additives and the barite are expected to provide a reasonable comparison of mudcake fabric enhancement potential of common mud additives. The pH of all the muds was adjusted to 9.8-10 to keep the pH-dependant variation of mudcake properties to a negligible level.

Development of Test Set-up

The assessment of mechanical properties of mudcakes on the basis of theoretical consideration will be difficult because of their dependency on many factors such as grain rearrangement, work hardening or softening, matrix fluid pressure build up or dissipation, changes in the mode of interactions of electrochemical forces etc. In this case, the best way to gather information regarding the mechanical properties of a mudcake is to conduct experimental study simulating the downhole conditions as closely as possible. Thus, testing of mudcakes in the laboratory under controlled conditions could provide valuable information regarding the behaviour of mudcakes deposited on the wall of a borehole. Bearing this in mind, a test facility and laboratory technique have been developed for experimental determination of embedment characteristics of mudcakes. The testing procedure is simple and easy to operate with full automation of the data recording process.

Figure 2 shows the schematic diagram of the test set-up developed for determination of embedment resistance of mudcakes. The core of the apparatus is a cylindrical foot indenter (4). The shape of the foot was selected to simulate the real borehole embedment situation as closely as possible. A Wykeham Farrance stepless compression machine (1) was used to drive the cylindrical foot into the mudcake matrix with a controlled rate of embedment. Several components were added to the test set-up to perform different functions (see Figure 2). These are an electronic balance (8) to record the embedment force as a function of time and depth, a digital dial gauge (2) to record the downward displacement of the foot, a lab jack (7) to place the API cell containing the mudcake (5) and raise it to the desired level before starting a test, and a PC-based automatic data logging system (10). A foot stem (3) was attached to the cylindrical foot to fix it to the loading yoke of the stepless compression machine (see Figure 3). The compression machine has a control box (11) to define and maintain a constant rate of indentation during the test period and also reverse the motion of the foot.

Experimental Procedure

After the filtration of designated amount of mud filtrate, the excess mud was decanted slowly to avoid any disturbance to the mudcake. Then the mudcake was washed gently to remove the gel-like top layers using static water without removing it from the API cell. Hence, there was negligible disturbance to the inner matrix of the mudcake. After washing the mudcake, the thickness of the mudcake was measured. There were some variations in the thickness of the mudcakes but all of them produced a cake thickness of more than 14 mm. The API cell containing the mudcake was placed on the lab jack after fixing a stopper at the filtrate outlet of the cell (Figure 2). This was done to prevent any cake matrix fluid expulsion at the bottom of the mudcake. Then the lab jack was placed on the electronic balance in such a way that the cylindrical foot just touches the extreme top of the mudcake. The rate of displacement of the foot was selected to be 0.25 mm/min using the rate control knob of the stepless compression machine. The constant rate of indentation of the cylindrical foot (see Figure 2) was used for all the tests to eliminate the rate-related variations of the driving force. To simulate the condition of progressive loading, the cylindrical foot was moved downward at the selected rate. At the beginning of the test, the dial gauge and electronic balance readings were zeroed. The test was continued until the cylindrical foot reached an approximate depth of 7.5 mm or a predefined value. The cylindrical shape of the foot caused a large displacement of mudcake surface at the centre of the cylindrical foot and a small displacement at the edge of the foot. During the test, the data was automatically recorded using a dedicated PC-based software.

Results and Discussion

Compared to the general behaviour of soil or rock-like materials, all the mudcakes have extremely low embedment resistance (see Table 2). This is due to the absence of any cementation bonding among the fabric forming units. Cementation bonding is formed between particles of soil or rock-like materials when they are under high pressure and temperature for a long geological period of time or due to cementation reaction of some chemicals such as lime. As the mudcakes were formed quickly in the absence of any cementation reaction, there was no scope of formation of cementation bonding between the particles or the flocs of the mudcakes. Hence, the strength and deformation properties of the mudcakes are solely dependent on the strength of the chemical bondings formed by the adsorbed water surrounded bentonite particles and other mud additives. The absence of any cementation bondings indicates that the strength of the mudcake fabric is the result of the action of electro-chemical, Van der Waal's and ionic forces.

Critical Embedment Depth

It was assumed that the stiff base of the API cell (see Figure 2) containing the mudcake will have no significant effect on the driving force below a critical depth of embedment. It was further assumed that the critical embedment depth of mudcakes of more than 14 mm thickness will represent at least 50% of the total mudcake thickness. To verify this hypothesis, four identical bentonite mudcakes having thicknesses between 14 to 16 mm were tested for four different embedment depths under the same experimental conditions. Analyses of the data of the four mudcakes (see Figure 3) indicate that the force required to drive the cylindrical foot into the mudcake is predominantly controlled by the structural rigidity of the mudcake matrix up to a critical depth of embedment. This is reflected by the presence of a characteristic signature in the driving force versus embedded depth curve of the mudcake, tested up to an embedment depth of 12.4 mm (see Figure 3). The break-point shown in the curve, representing the transition from concavity upward to apparent linearity, is the critical embedment depth. Above this signature point, the curve shows an apparent linear relation between the driving force and the downward displacement of the cylindrical foot and below this signature point, a non-linear relation with an upward concavity in the driving force versus embedded depth curve. The hypothesis is further supported by the driving force vs. embedment depth graph shown in Figure 4. The shifting away of the last data point from the fitted regression line and the close proximity of other data points to the regression line illustrate that the critical depth of embedment is below 10 mm for mudcakes having a thickness above 14 mm. The first three data points also indicate strong linearity and thus, are expected to have a negligible base effect. Thus, the conservative estimate of the critical depth of embedment is taken as 7.9 mm which is about 54% of the thickness of the thinnest mudcake (14.5 mm). Beyond the critical embedment depth, the curve shows progressively rapid rise in the driving force due to the increasingly higher influence of the stiff base of the API cell. On the basis of this observation, it was decided to prepare mudcakes in such a way that the thickness of all the mudcakes lies above 14 mm. The depth of embedment for comparative study of different mudcakes was selected to be 7.5 mm which is slightly below the conservative estimate of the embedment depth.

The authenticity of the newly developed testing method is reflected by the similarity of physio-mechanical behaviour of the four bentonite mudcakes. The similar load-displacement paths and nearly identical slope of the four test curves (see Figure 3) confirm that all the mudcakes have similarities in their composition and depositional environments. The slight variation of the slopes is assumed to have a negligible effect on the overall assessment of the mudcakes behaviour and for all practical purposes, the slope of the four different bentonite mudcakes may be considered identical without introducing any significant errors (see Figure 3).

Effect of pH

Figure 5 shows the driving force versus embedded area curve of bentonite mudcakes deposited under four different pH environments. As the magnitude and nature of the electro-chemical and other molecular forces strongly depend on the pH or alkalinity of muds, it was required to check the variations of the driving forces needed to reach the same embedment depth for bentonite mudcakes formed under different pH conditions of the muds. The results indicate some variation in the driving forces at an identical embedment depth/areas due to a change in the pH of the muds. This variation is higher with a higher difference in pH values of the muds. To minimise this pH-dependant variation, pH of all the muds used for this study was adjusted to within the range of 9.8 to 10.

Comparison of Driving Force-Embedment Area Characteristics

Figures 6–12 show the driving force versus embedded area curves obtained by testing three to four identical mudcakes formed by different mud systems. All the mudcake curves show the same characteristic shape but different magnitude of driving force required to reach a particular embedment depth. Previous data presented in Figure 3 confirmed that for a constant geometrical shape and rate of driving of the foot, the shape of the driving force vs. embedment area curve of the mudcakes is dictated by the mechanical properties of the mudcakes up to and below the critical embedment depth. As all the tests were performed identically using the same test conditions, the possible stiff base effect (if any) is assumed to be an unknown constant of a negligible magnitude. The shape of each of the curves of the mudcakes indicates the presence of a strength parameter proportional to the matrix rigidity of the respective mudcakes.

All the curves have an apparent initial linear part followed by a non-linear part of upward concavity due to an exponential growth in driving force with increasing depth of embedment. The initial linear part represents the top visco-plastic material which has high lateral distortion, higher degree of spatial orientation and matrix fluid dissipation. The later part represents the inner matrix of the mudcakes which has a higher packing density, a lower lateral distortion and a higher restriction to matrix fluid dissipation. The progressive in-situ realignment of particles, increase in fabric strength due to work hardening effect and the build-up of higher matrix pressure with increasing depth also cause an increase in embedment resistance of the mudcake. In some cases, the results of the three tests approximately follow the same load-indentation path (see Figures 6-12) and in most cases, two of the test results show nearly similar behaviour. Considering mechanical nature of mudcakes, the results, in general, shows reasonable reproducibility. Some dispersion of the data is expected due to soil-like behaviour of mudcakes. It is suggested to carry out three tests in case of significant difference between the first and second tests to find a reasonable average. Some variations could be the result of a difference in the depositional environment of the mudcake, degree of dispersion/flocculation of the mud additives during the period of deposition and also operator's error associated with the cake washing.

Figure 13 shows a definite compositional influence caused by a change in the nature of mud additives present in the mud systems. All the mudcakes show a little increase in the driving force at the initial stage of the tests and there is a much less difference in the behaviour of the mudcakes at this stage in spite of the same differences in the chemical composition of the mudcakes. The data further show that the difference in behaviour increases with increasing depth of indentation. The top layer of the mudcakes is more likely to be close to the liquid limit of the materials. Hence, the fabric units are poorly defined in the top layer of the mudcakes. As the fabric structures are in a pseudo-dispersed state near the liquid limit, there is little structural resistance to the indenter at this part of the mudcake. For this reason, in spite of the same degree of chemical variation of the mudcakes, there is little difference in their resistance to the indenter. This is reflected by the less divergence of the curves at the early stage of the test. After this initial stage, the curves show a higher increase in the driving force with progressively higher divergence with increasing depth of embedment. The deeper layer of the mudcakes is sifting away from the liquid limit and approaching more and more to the plastic limit. Due to the changing of the physical state of the deeper layer compared to the surface layer, the mud additives are able to form well defined fabric units with a good structural rigidity. For this reason, the mechanical effect of the mud chemistry is more pronounced at the later stage of the test which is reflected by the pronounced divergence of the curves.

Even though, all the curves show the same general pattern, in some cases, the driving force is several times higher when compared at an equal depth of embedment e.g. the driving force for bentonite or barite-bentonite mudcakes is about 2 to more than 3 times higher compared to the NaCl-bentonite mudcake. In other instances, there are little differences in the driving force at the same embedment depth e.g. bentonite and KCl-bentonite mudcakes or barite-bentonite and NaCl-bentonite-PAC mudcakes (see Figure13). The identical pattern of the driving force versus embedded area curves indicates that the same physical law governs the behaviour of mudcakes under the test conditions. The difference in the magnitude of the driving force indicates that the nature of the mud additives governs the matrix rigidity of the mudcakes.

Definition of Embedment Modulus

The presence of a built-in strength parameter in all the curves in proportion to the fabric strength of the mudcakes enables the use of an index parameter based on the slope of a well defined part of the curves for comparative study of the mechanical characteristics of mudcakes formed by different mud systems. The behaviour of the surfacial part of the mudcakes depends not only on the chemical composition of the mudcake but also on the presence of a gel-like soft layer and the detrimental effect of the water used to wash the mudcakes. From this point of view, the slope of the apparently linear initial part of the curves will not be an appropriate index parameter for the assessment of mudcakes formed by different mud systems. However, a satisfactory and representative index parameter can be obtained if it is based on readings taken beyond the initial linear part of the curves. Due to the predominantly non-linear shape of the curves after a short initial linear part (see Figure 6-12), the secant slope of a well defined concave part of the curves will provide an appropriate index parameter. Bearing this in mind, an index parameter defined as 'embedment modulus' (EM) was determined for different mudcakes using the secant slope of the line passing through the origin and the point of the curve corresponding to 1000 mm^2 embedded area (5.75 mm embedment depth). The embedment moduli of the mudcakes are given in Table 2. The arbitrarily selected 5.75 mm embedment depth (1000 mm^2 embedded area) is about 40% less than the depth representing the characteristic signature point (about 9.6 mm, see Figure 3) and about 23% less than the selected embedment depth (7.5 mm) of testing. A conservative approach was taken to determine the EM of mudcakes to avoid any scope of non-compositional variation with a strong focus on the minimisation of the stiff base effect of the API cell.

Comparison of Embedment Modulus

Analyses of the EM value (see Table 2 and Figure 13) of the mudcakes indicate that the bentonite mudcakes, deposited in a pH environment of 10, has an average EM value similar to that of the mudcake formed by a KCl-bentonite mud. Bentonite particles possess a complex electrical field environment due to the presence of negative charges at the surface and positive charges at the edges. The condition of the particles in the mud system is governed by the nature of the net effective force. In this pH environment, the resultant effect of the interaction forces is repulsive. Due to the existence of the net repulsive force during the deposition of the particles, they form a mudcake with well dispersed and homogeneous fabric structures having a high packing density and a low permeability. Moreover, the hydrated bentonite particles have high cohesive bonding potential due to the inter-play of other molecular forces. This provides a higher structural rigidity of the mudcake fabric and thus, the higher EM compared to those of NaCl-bentonite, NaCl-bentonite-CMC and NaCl-bentonite-starch mudcakes.

Barite-bentonite mudcake showed the highest embedment resistance which is reflected by the highest average EM value of this mudcake. The barite particles, acting as fillers, reduce the porosity and permeability of the mudcake and increase the structural rigidity of the fabric units. The mass adhesion property of barite particles also increases the inter-particle bonding of the mudcake material. For these reasons, the driving force required to push the cylindrical foot to the target depth is higher for barite-bentonite mudcake compared to those of the other mudcakes.

KCl-bentonite mudcake has a higher EM than NaCl-bentonite mudcake but similar to that of bentonite mudcake. The higher EM value compared to NaCl-bentonite mudcake is understandable but its similar value to that of bentonite mudcake is difficult to explain. The higher EM of KCl-bentonite mudcake compared to the NaCl-bentonite mudcake is due to the lower hydrated ionic diameter of the K^+ ions compared to Na^+ ions. Due to lower hydrated ionic diameter and better fixation of the ions between bentonite layers, the deposited KCl-bentonite mudcake has higher packing density and consequently a lower permeability than the NaCl-bentonite mudcake. However, as the flocculation of bentonite in the presence of KCl facilitates the deposition of bentonite particles in the form of flocs, it was expected to give a lower EM than the bentonite mudcake. This anomaly could be the result of collapse hardening of the mudcake matrix during the driving of the cylindrical foot. Two of the three tests, show the indication of collapse hardening of the mudcake (see Figure 7). In fact, the third test which shows no indication of collapse hardening, produced a lower EM than that of the bentonite mudcake. It will not be feasible to draw further conclusions without additional testing of the mudcakes under the same test conditions.

NaCl-bentonite mudcake shows the lowest embedment resistance and thus the EM among the mudcakes tested except the NaCl-bentonite-starch mudcake. The presence of electrolyte significantly reduced the repulsive forces between bentonite particles and thus generated a net attraction force in the mud systems. The attractive forces of interactions facilitated the flocculation of bentonite particles in the mud system. The deposition of the flocs made the mudcake highly porous with the formation of a relatively flexible and easily collapsible honey-comb like fabric structures. The presence of macro-voids in the mudcake matrix is an indication of honey-comb like structures. For these reasons, the mudcake has a low embedment resistance. The drilling engineering significance of this observation is that settled cuttings could easily create an embedded cuttings bed in the presence of such mudcakes. Drill string will likely to embed deeper into the mudcake under the same bending and dog leg severity conditions and will require relatively higher torque and drag.

NaCl-bentonite-CMC mudcake produced an embedment resistance somewhat higher than that of NaCl-bentonite mudcake but significantly lower than that of NaCl-bentonite-PAC mudcake. The anionic CMC has caused some reduction in the flocculating action of NaCl leading to a higher matrix rigidity of the mudcake compared to the NaCl-bentonite mudcake. Due to its significantly lower deflocculating potential than the polyanionic polymer (PAC), the degree of mudcake fabric enhancement is quite low compared to PAC. The slight increase in the structural resistance of the NaCl-bentonite-CMC mudcake is partly due to the adsorption of the CMC onto the negatively charged surfaces of bentonite and partly due to the reduction in matrix porosity and permeability of the mudcake. From a mechanical point of view, the fluid loss additive CMC has little contribution in enhancing the matrix rigidity of the mudcake.

NaCl-bentonite-PAC mudcake produced a much higher embedment resistance compared to those of NaCl-bentonite, NaCl-bentonite-starch and NaCl-bentonite-CMC mudcakes and a significantly higher resistance than those of bentonite and KCl-bentonite mudcakes. In fact, it gave EM value comparable to barite-bentonite mudcake. The presence of polyanionic cellulose PAC caused a significant increase in net repulsive force and thus reduced or neutralised the flocculating potential of the electrolyte. The existence of a net repulsive force of interactions in the mud during the period of deposition creates a mudcake with dispersed structure. In addition, the random entanglement of other particles in the mudcake by the polymer chains creates fabric units with a higher structural rigidity. This type of fabric structures has a better load bearing capacity than honey comb or card house-like structures. The deposition of mud additives in a dispersed manner together with the generation of effective bonding after deposition due to the inter-play of other forces of interactions made the mudcake matrix stronger. The attachment of polyanionic PAC to the negatively charged surfaces of bentonite also facilitated face-to-face association of the bentonite particles with the generation of a higher structural rigidity and thus a higher EM value.

The NaCl-bentonite-starch mudcake indicates no improvement of mudcake matrix rigidity in the presence of modified starch which is reflected by an EM value nearly equal to that of NaCl-bentonite mudcake. In fact, it gave the lowest EM value among all the mudcakes tested. The non-ionic modified starch on contact with the bentonite particles tends to spread over their surfaces and creates a weak physical barrier for bentonite to bentonite flocculation by the cations of the electrolyte. Due to physical nature of shielding of mud additives, there is a little reduction in the net attractive forces in the mud system. For these reasons, the particles deposited in a highly flocculated state with the formation of a crumb-type mudcake matrix. The physical nature of bonding of starch with the bentonite particles compared to the electro-chemical and physical nature of bonding of CMC and PAC with bentonite particles made the mudcake matrix less resistive to embedment. The mechanical disadvantage of physical adsorption of non-ionic starch over ionic adsorption of CMC and PAC made the fabric units of the NaCl-bentonite-starch mudcake flexible, mechanically weak and easily collapsible. This is reflected by the lowest EM of the mudcake.

Variation in Test Results

Due to the variation in the nature of mudcake fabric formation during the deposition of mudcake materials and damaging of the mudcake during washing and handling, there would be some variations in the test results. These variations can be minimised for any practical purposes by taking extra care during the preparation and testing of mudcakes. Error may also arise due to the lack of proper accounting for load and displacement-related offset values. The offset load is the result of the self-weight of the digital dial gauge foot when it touches the electronic balance. During the testing, the offset value of driving force may fluctuate within a range due to mechanical influences predominantly related to vibration. In this case, the maximum fluctuated load should be taken as the offset value. The offset displacement value should be added to the predefined embedment depth and the test should be continued until the cylindrical foot reaches total depth so as to ensure an identical depth of embedment for all the mudcakes. The offset displacement may change from test to test even for tests performed by the same operator.

The dispersion of the test results has been checked by performing five tests on bentonite mudcakes formed under a pH environment of 9, four tests on bentonite mudcakes formed under a pH environment of 10 and four tests on mudcakes formed under a pH environment of 11. The results of the statistical analyses are given in Table 4. In spite of the scope of the operator-related errors, the results indicate a coefficient of variation of less than 10%. Part of this error can be eliminated by taking extra care during sample preparation and testing. Since quantitative analyses in rock, soil and similar materials do not have the precision sought in other branches of engineering, at least three tests should be carried out on each type of mudcakes to find a reliable average of the embedment modulus of mudcakes. If one of the three tests give a markedly different result, another test should be conducted to produce a reliable information on the behaviour of the mudcake.

Technico-Economical Significance of Embedment Modulus

High embedment modulus of mudcakes ensures that any cuttings bed that formed will be less impregnated into the mudcake matrix. This will facilitate the easy return of cuttings to main stream flow under the action of hydrodynamic forces of mud flow and pipe movement and thus better hole cleaning capacity compared to those muds which form mudcakes of lower embedment modulus. Removal of embedded cuttings will reduce the scope of pressure losses in the annulus and thus may allow higher annular flow velocity by extending the ECD limit for a particular drilling condition. The likelihood of forming a thick mudcake due to the formation of an impregnated cuttings bed will also be less in the presence of high EM mudcakes and thus, it is expected to reduce the scope of differential sticking in areas highly prone to differential pressure sticking problem. The lower concentration of embedded cuttings will also reduce the tendency of mechanical stuck pipe problems by reducing the mudcake thickness and maintaining its inherent lubricity. It may be mentioned that the lubricating property of mudcake to the pipe interface reduces significantly with the formation of embedded cuttings bed. Mudcakes with higher EM values will also provide better hole stability, especially in the poorly consolidated sand sections of a borehole.

In the case of encountering excessive torque and drag during drilling or tripping, mud additives such as walnut hulls or glass beads are added to the mud system to increase the lubricity of the mudcake. In this case, the walnut hulls or glass beads resting on the mudcake surface act as ‘ball bearing’ and thus reduce the torque and drag. The effectiveness of lubrication and sliding effect of the beads depend on the degree of embedment of the beads which is directly related to the embedment modulus of the mudcake. Complete embedment of the beads into the mudcake matrix reduces the lubricating efficiency of the beads. Hence, designing of a drilling mud with the potential to deposit a mudcake of higher embedment modulus will increase the effectiveness of these mud additives. Furthermore mudcake with a higher embedment modulus will offer higher resistance to stabiliser digging of mudcake. This will reduce mechanical erosion of mudcake and hence, expected to reduce the potential of formation damage.

Cake-related borehole problems can significantly increase the cost of drilling due to a loss in drilling time and addition of an undesirable cost to the total drilling expenditure, associated with the reduced rate of penetration, rescue job, side tracking and/or abandonment of a well. Pipe stuck problem may interrupt the drilling progress for days or even weeks and sometimes may lead to the abandonment of the well. The problem of torque and drag will cause a significant loss of rig power with an increase in the daily running cost. Mud forming mudcakes with higher embedment resistance could significantly alleviate this unwanted power loss and non-productive drilling cost. This highlights the economical significance of the mechanical properties of mudcakes. Hence, a prior knowledge of the mechanical characteristics of mudcakes formed by different mud systems can provide valuable information in selecting or designing a mud for highly permeable formations, deviated or horizontal boreholes, slimhole and coiled tubing drilling. A decision to design or select a mud on the basis of the mechanical property of mudcake as one of the critical factors reflect the technico-economical and drilling engineering significance of the index parameter EM.

The EM index parameter can conveniently be used for classification/categorisation of mudcakes (see Table 3). The quantitative method of classification will be more reliable and less subjective, and thus expected to be a better method of classification compared to the currently used qualitative method. Although the boundary values between classes/categories were selected arbitrarily, full consideration of possible mud consistencies were taken in fixing the boundary limits. The classification can be extended and modified by determining the EM value of mudcakes formed by different mud systems currently available in the market.

Conclusions

1. The newly developed laboratory technique and test facility provide a suitable, easy to operate and quick method for determining the embedment characteristics of mudcakes. The technique provides a more reliable and accurate method to group different mudcakes into various categories according to their mechanical characteristics.
2. Cake matrix structural variation and the composition of the cake forming mud additives are important factors that govern the embedment resistance of mudcakes. Mudcakes with high structural rigidity need higher driving force to reach the same embedment depth compared to those with lower structural rigidity.
3. The presence of a built-in strength parameter in driving force versus embedded area curves enables the use of the slope of a suitable part of the curves as an index parameter for comparative assessment of mudcakes. The use of secant modulus seems to be an appropriate approach in analysing the mechanical characteristics of mudcakes formed by different mud systems due to the non-linear relation of the driving force versus embedded area of the mudcakes.
4. Although the magnitude of the driving force and the embedment modulus are different for different mudcakes, the driving force versus embedded area curve of all the mudcakes showed the same characteristic features. This illustrates that the behaviour of the mudcakes obeys the same physical law.
5. The present study indicates that barite-bentonite mudcake has the highest embedment modulus followed by NaCl-bentonite-PAC mudcake. Bentonite and KCl-bentonite mudcakes have the third highest embedment modulus which are much higher than that of NaCl-bentonite mudcake. NaCl-bentonite-CMC mudcake has an embedment modulus closer to that of NaCl-bentonite mudcake. The presence of modified starch resulted in no

change in the EM of mudcakes formed by a NaCl-bentonite mud.

6. The various boundary limits of the designated categories are purely arbitrary. They were defined by the values of the EM of mudcakes formed by various mud systems. The parameter EM provides a practical means for classifying mudcakes into categories such as very hard, hard, soft, very soft etc.

7. The suggested ratings and classifications can be modified, upgraded or extended by determining the embedment moduli of different mudcakes under similar test conditions. This method of mudcake categorisation should be more reliable as the risk of human errors associated with visual observation or crude assessment with the finger tip will be eliminated.

8. From a mechanical point of view, the presence of some polymeric fluid loss additives in the mud causes an improvement in the fabric structures and thus the embedment modulus of mudcakes. The presence of such polymers in a mud system is expected to offer greater resistance to pipe embedment and impregnated cuttings bed formation.

9. One of the corrective measures to reduce the potential of impregnated cuttings bed formation or to reduce the scope of pipe sticking problem is to design and formulate a mud system capable of producing a mudcake with a higher embedment modulus.

10. The data show that salt water muds containing polyanionic polymer PAC form mudcake with higher matrix rigidity than muds containing anionic CMC. The high embedment modulus of the mudcakes indicate better inter-particle bonding potential of the polyanionic polymers PAC.

Acknowledgements
The authors cordially acknowledge the financial support provided by CSIRO Petroleum for this project. Special thanks to Steve Tsaganas and Michael Camilleri for their help in executing this project.

References

1. Harden, E. L., and Welch, G.R.: Techniques for Preventing Differential Pressure Sticking of Drill Pipe. Paper presented at southern Dist. API, Shreveport, LA, (March 10, 1961)
2. Amanullah, Md. and Tan, C.P. : A Non-Destructive Method of Cake Thickness Measurement, SPE Asia-Pacific Oil & Gas Conference and Exhibition, Brisbane, Australia 16-18 October, 2000, SPE 64517.
3. Reid, P.I., Meeten, G.H. Way, P.W., Clark, P., Chambers, B.D., Gilmour, A. and Sanders, M.W. : Differential-Sticking Mechanisms and a Simple Wellsite Test for Monitoring and Optimizing Drilling Mud Properties, SPE Drilling and Completion 15 (2), June 2000.
4. Isambourg, P. and Marti, J.: “Down-hole simulation cell for measurement of lubricity and differential pressure sticking”, SPE/IADC Drilling Conference, Amsterdam, Holland, SPE/IADC 52816 (1999).
5. Warren, J .E. : Causes, Prevention and Recovery of Stuck Pipe, Drilling and Production Practice, API, 1940.
6. Maidla, E.E.: “Borehole friction assessment and application to oilfield casing design in directional wells”, Ph.D. Thesis, Louisiana State University (1987).
7. Davis, N., Mihalik, P., Lundie, P.R. and Davidson, E. : New Permeability Plugging Procedure Addresses Safety and Technology Issues. SPE/IADC Drilling Conference, Amsterdam, Holland, 9-11 March, 1999, SPE/IADC 52815

Table 1 Composition of the muds used for the study

Mud Additives	Bentonite Mud	Barite-Bentonite Mud	NaCl-Bentonite Mud	KCl-Bentonite Mud	NaCl-Bentonite-PAC Mud	NaCl-Bentonite-CMC Mud	NaCl-Bentonite-Starch Mud
Water ml	350	350	350	350	350	350	350
Bentonite ppb	30	30	30	30	30	30	30
Barite ppb	-	200	-	-	-	-	-
NaCl ppb	-	-	35	-	35	35	35
KCl ppb	-	-	-	35	-	-	-
PAC ppb	-	-	-	-	2	-	-
CMC ppb	-	-	-	-	-	2	-
Starch ppb	-	-	-	-	-	-	2
NaOH to Raise pH to 10	As Required	As Required	As Required	As Required	As Required	As Required	As Required

Table 2 Driving Force @ 1000 mm^2 Embedded Area and Average EM of Mudcakes

Type of Mudcakes	Driving Force (gmf)					EM (gmf/mm^2)
	Test 1	Test 2	Test 3	Test 4	Mean	
Bentonite Mudcake, pH 10	237.0	255.0	211.0	266.0	242.3	0.24
Barite-Bentonite Mudcake	397.0	361.0	357.0	-	371.7	0.37
KCl-Bentonite Mudcake	255.0	192.0	274.0	-	240.3	0.24
NaCl-Bentonite Mudcake	133.0	111.0	112.0	-	118.7	0.12
NaCl-Bentonite-CMC Mudcake	182.0	156.0	120.0	-	152.7	0.15
NaCl-Bentonite-Starch Mudcake	121.0	92.0	123.0	-	112.0	0.11
NaCl-Bentonite-PAC Mudcake	353.0	377.0	339.0	-	356.3	0.36

EM = Embedment Modulus

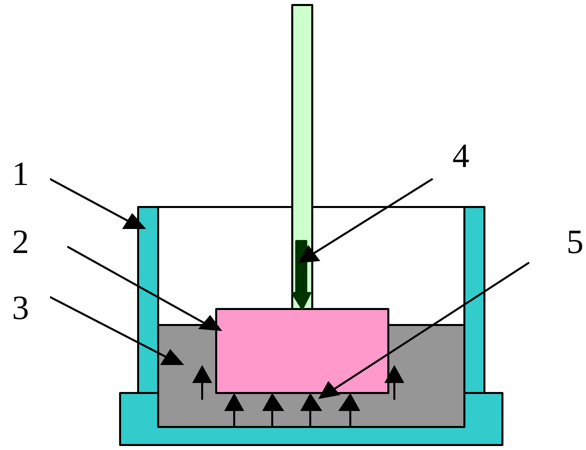
Table 3 Ranking of Mudcake Consistency on the Basis of Embedment Modulus

Embedment Modulus (gmf/mm^2)	Embedment Resistance	Example	Consistency Ranking
< 0.10	Extremely Low	-	Extremely Soft
0.10 – 0.15	Very Low	NaCl-Bentonite and NaCl-Bentonite-Starch Mudcakes	Very Soft
0.15 – 0.20	Low	NaCl-Bentonite-CMC Mudcake	Soft
0.20 – 0.25	Medium	Bentonite and KCl-Bentonite Mudcakes	Medium Hard
0.25 – 0.30	Moderate	-	Moderately Hard
0.30 – 0.35	High	-	Hard
0.35 – 0.40	Very High	Barite-Bentonite and NaCl-Bentonite-PAC Mudcakes	Very Hard
>0.40	Extremely High	-	Extremely Hard

Table 4 Statistical Analyses of Bentonite Mudcake Results

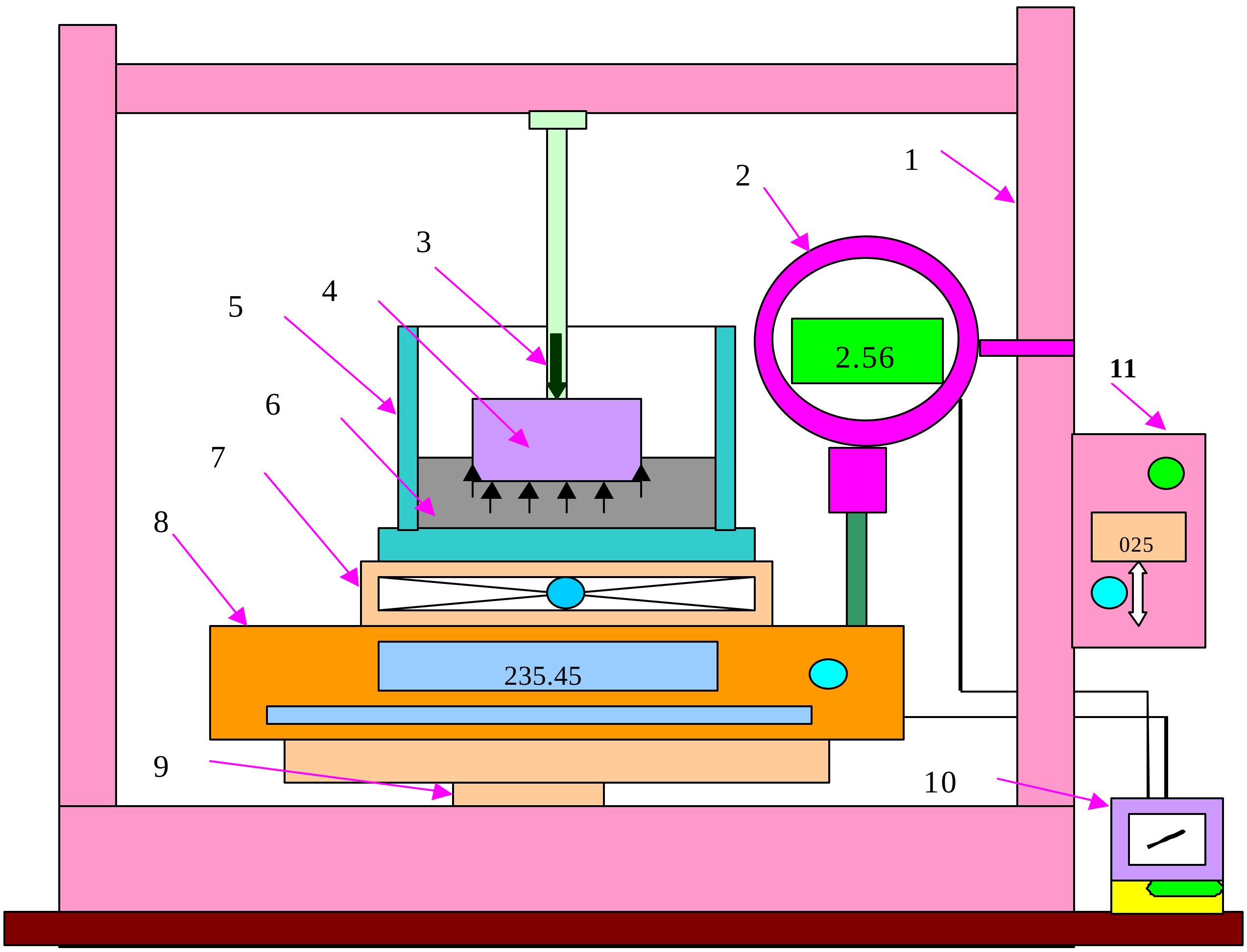
Type of Mudcake	Driving Force @1000 mm^2 Foot-Mudcake Contact Interface (gmf)						SD	CV
	Test 1	Test 2	Test 3	Test 4	Test 5	Mean		
Bentonite Mudcake, pH 9	223.0	207.0	197.0	217.0	225.0	213.8	11.7	5.5
Bentonite Mudcake, pH 10	237.0	255.0	211.0	266.0	-	242.3	24.0	9.9
Bentonite Mudcake, pH 11	291.0	280.0	274.0	300.0	-	286.3	11.6	4.0

SD = Standard Deviation CV = Coefficient of Variation



1 - API Cell 2 – Cylindrical Foot 3 – Mudcake
4 – Pushing Force 5 – Embedment Resistance Force

Figure 1. Schematic Diagram of Embedment Resistance



1 – Wykeham Farrance Stepless Compression Machine 2 – Digital Dial Gauge
3 – Connecting Rod 4 – Cylindrical Foot Indenter 5 – API Filtration Cell
6 – Mudcake 7 – Lab Jack 8 – Electronic Balance 9 – Movable Base
10 – Automatic Data Logging System 11 – Power and Control Panel

Figure 2 Schematic Diagram of the Test Set-up

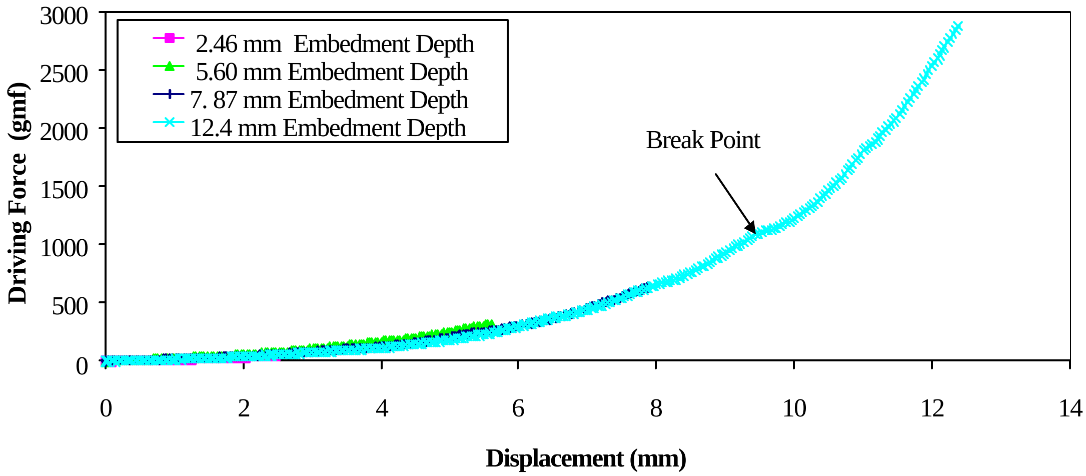


Figure 3 Driving Force versus Displacement with Different Depth of Embedment (Bentonite Mudcake)

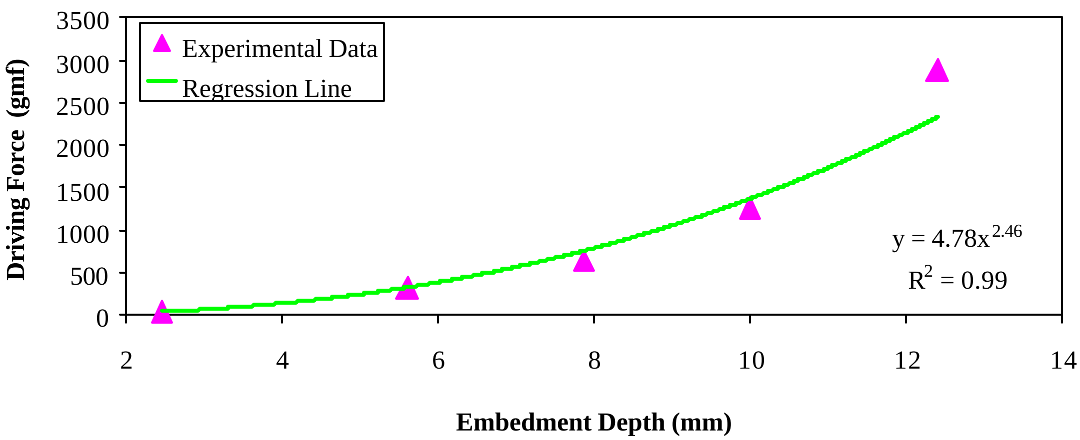


Figure 4 Driving Force versus Embedment Depth

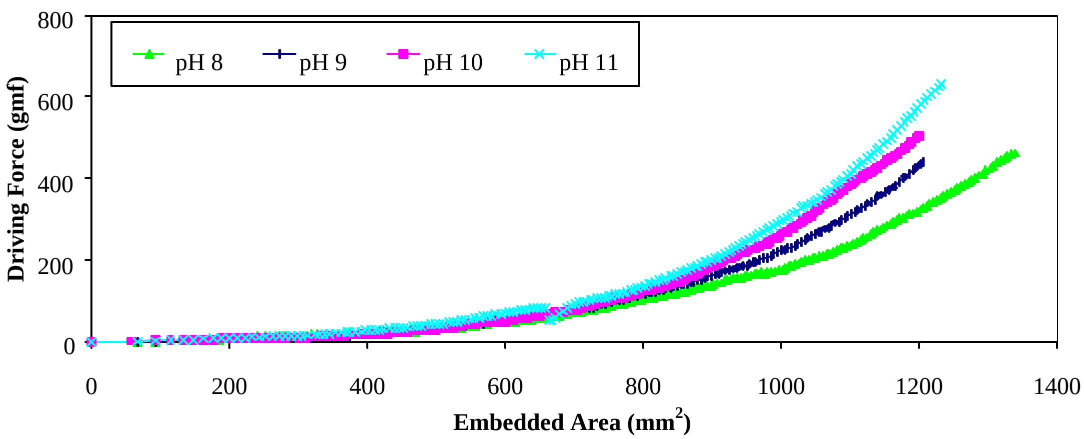


Figure 5 Driving Force versus Embedded Area for Different pH values of Mud

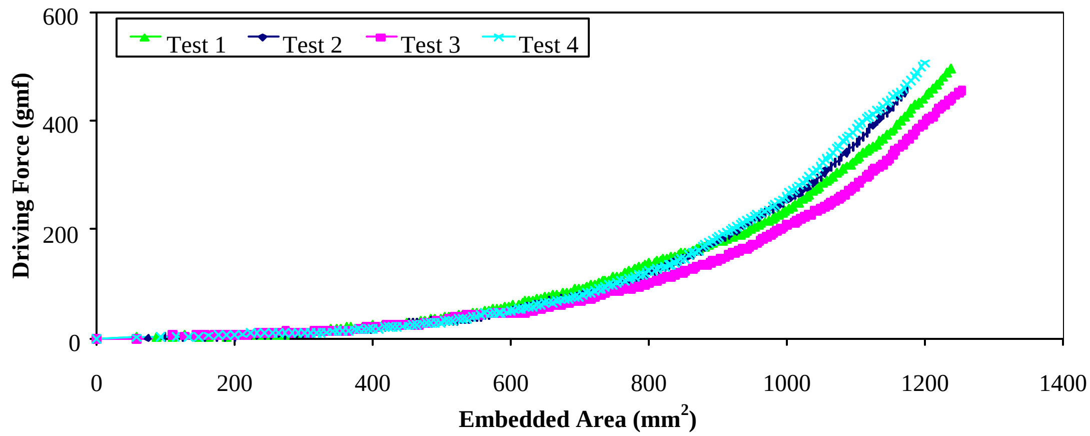


Figure 6 Driving Force versus Embedded Area (Bentonite Mudcake)

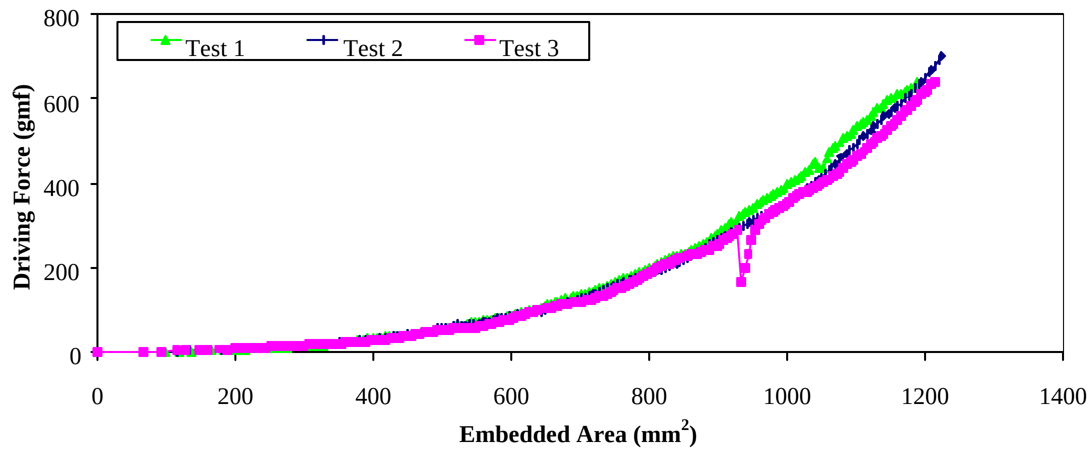


Figure 7 Driving Force versus Embedded Area (Barite-Bentonite Mudcake)

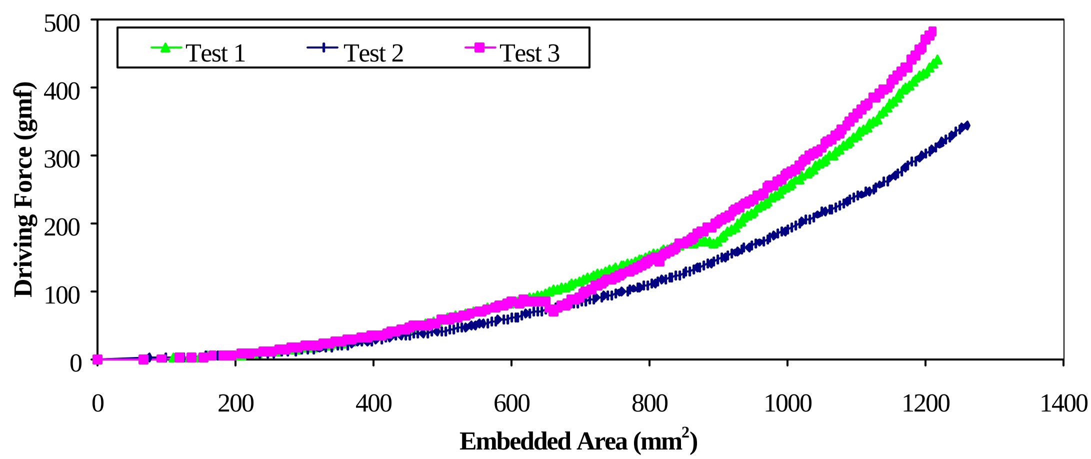


Figure 8 Driving Force versus Embedded Area (KCl-Bentonite Mudcake)

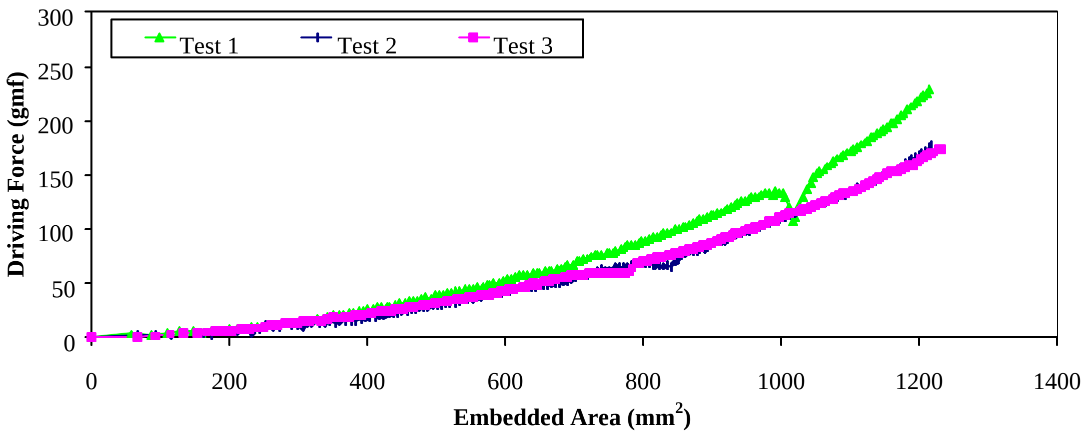


Figure 9 Driving Force versus Embedded Area (NaCl-Bentonite Mudcake)

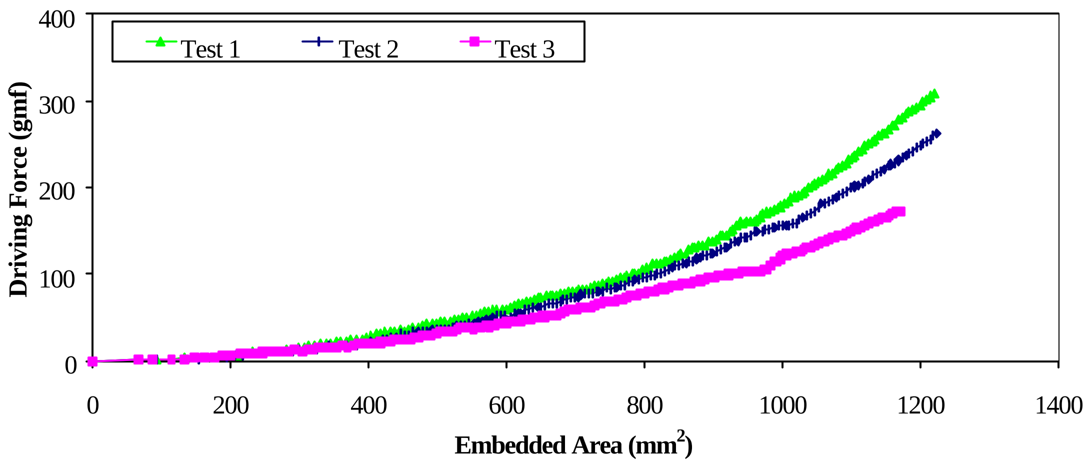


Figure 10 Driving Force versus Embedded Area (NaCl-Bentonite-CMC Mudcake)

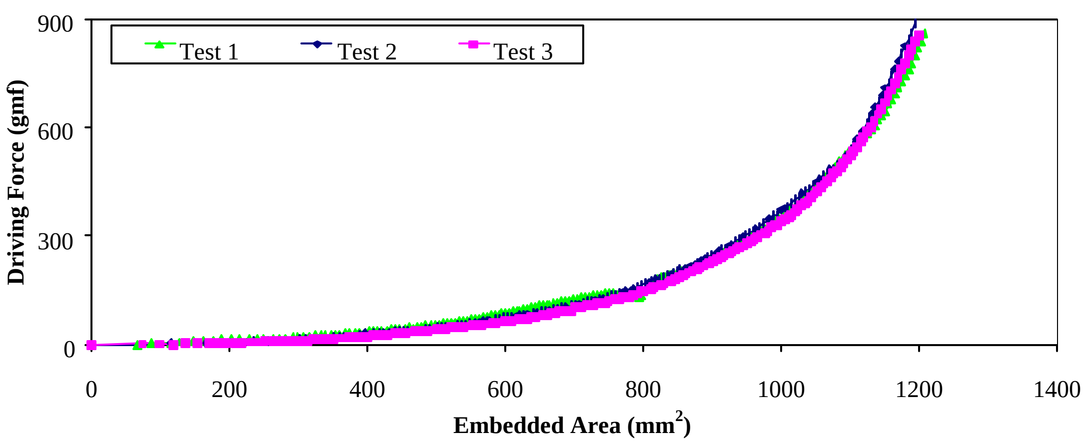


Figure 11 Driving Force versus Embedded Area (NaCl-Bentonite-PAC Mudcake)

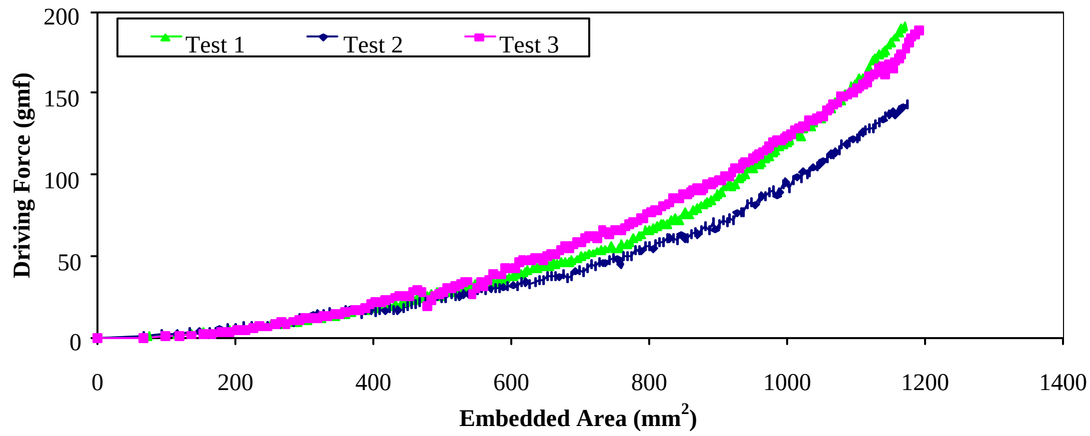


Figure 12 Driving Force versus Embedded Area (NaCl-Bentonite-Starch Mudcake)

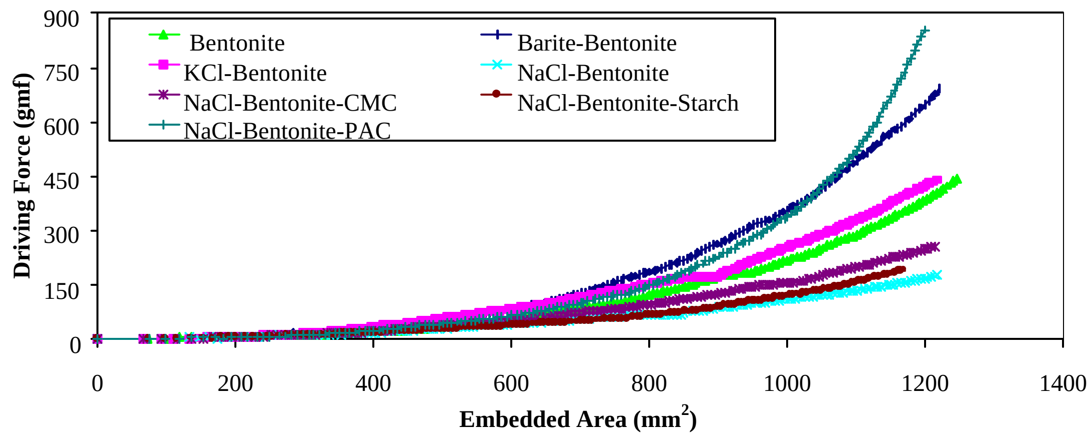


Figure13 Driving Force versus Embedded Area Curves of Different Mudcakes

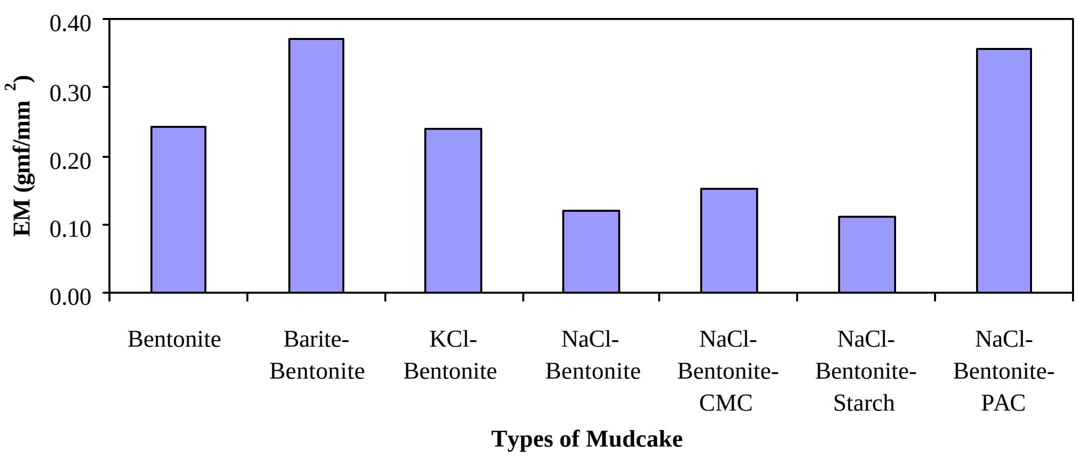


Figure14 Embedment Modulus of Different Mudcakes